

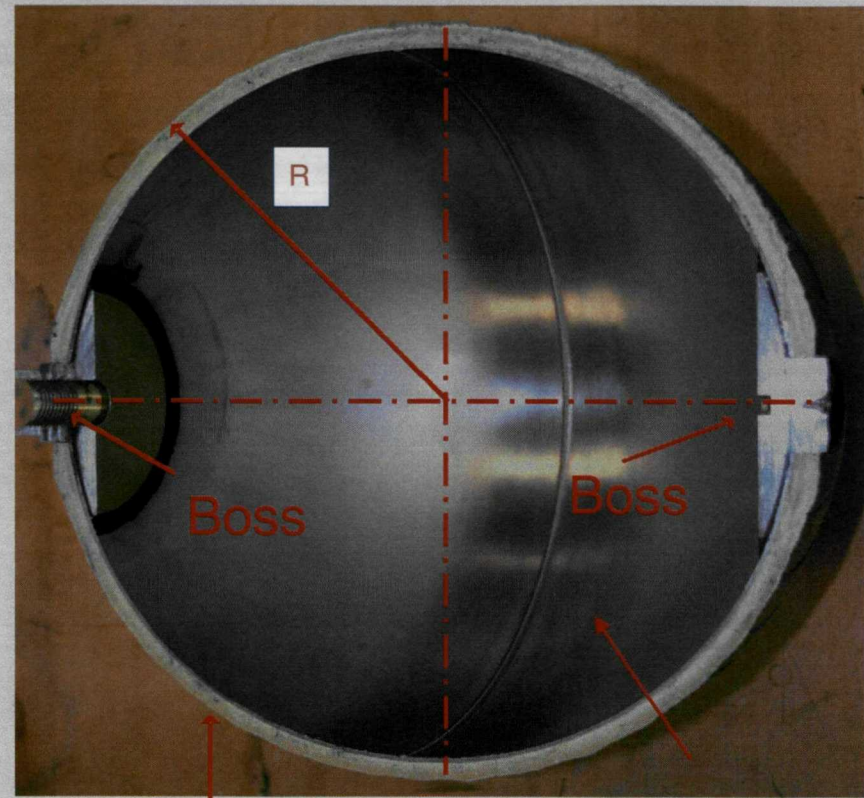
Composite Overwrapped Pressure Vessels (COPV) Materials Aging Issues

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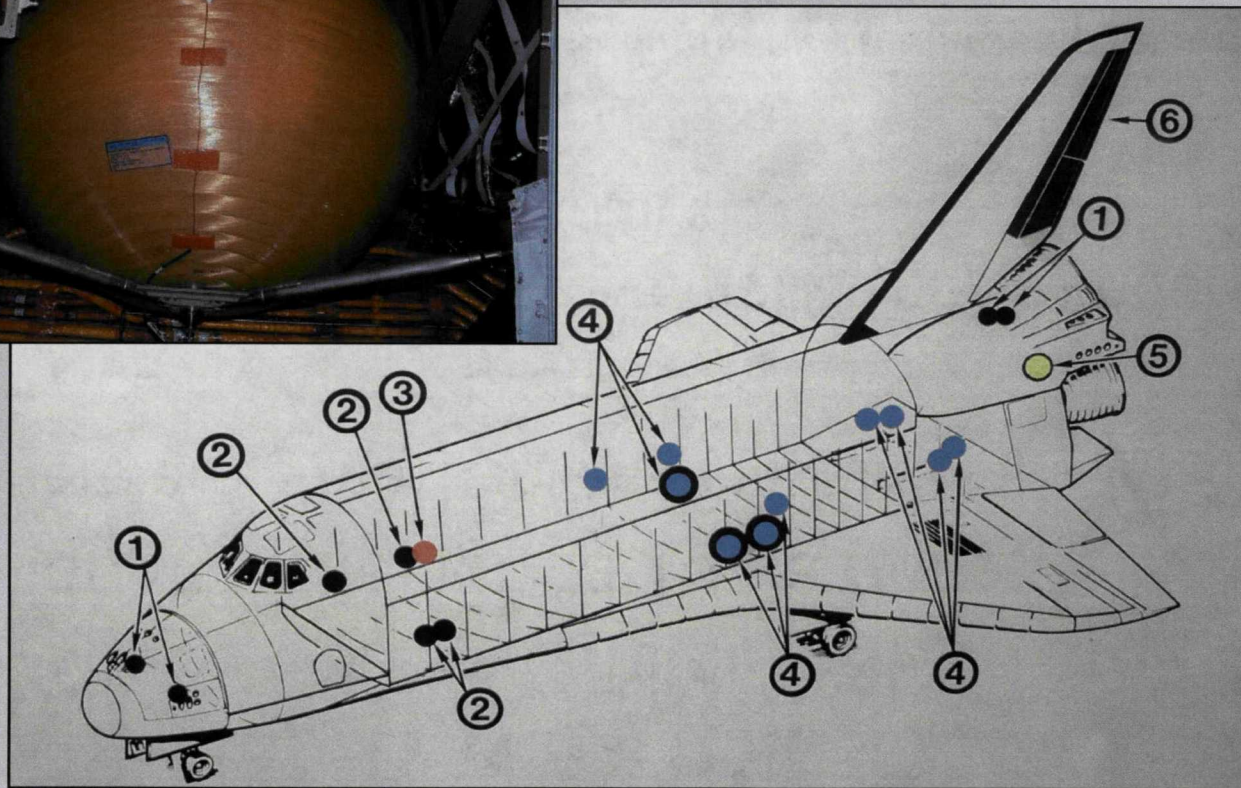
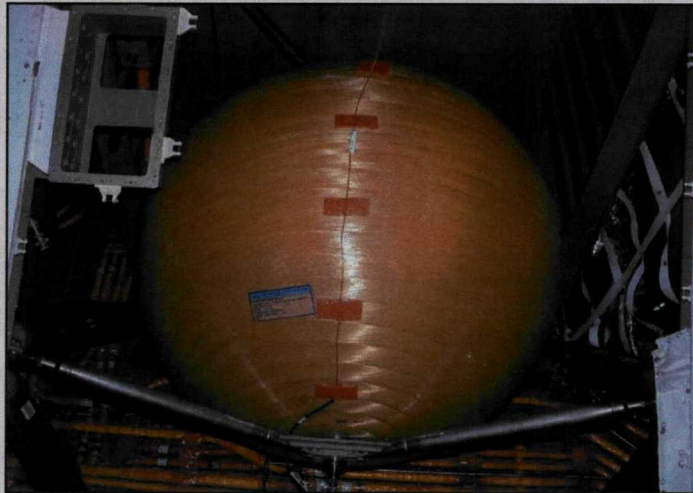
What is a COPV?

- NASA Orbiter Pressure Vessel
- Need was a light weight high strength pressure vessel
- NASA COPV was designed in 1970's
- Basic Composition:
 - Boss
 - Composite Overwrap
 - Metallic Liner
- Safety is key factor



Composite Overwrap

Metallic Liner



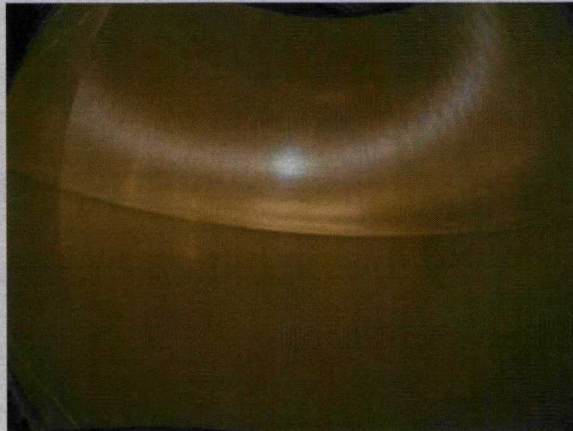
- The Space Shuttle Orbiter COPVs are operating outside their designed 10 year life.
 - There are 3 mechanisms that affect the life of a COPV
 - Age life of the overwrap
 - Cyclic fatigue of the metallic liner – understood through test and analysis
 - Stress Rupture life
 - Stress Rupture is a sudden and catastrophic failure of the overwrap while holding at a stress level below the ultimate strength for an extended time.
 - Currently there is no simple, deterministic method of determining the stress rupture life of a COPV, nor a screening technique to determine if a particular COPV is close to the time of a stress rupture failure.

- Orbiter is the oldest application for Kevlar/epoxy composite
- Initial Age-life testing in 1980s found no issues
 - 10 year old samples
 - Test data not saved
 - Orbiter COPV data packs not available

- Why do coupon tests?
 - Burst test represents a single failure point and not a rigorous measure of aging
 - Also no correlation between burst strength and stress rupture

- Composite testing
 - Strands tests (tensile/creep)
 - Stress rupture of strands
 - Transverse compression (squish)
 - Dynamic mechanical analysis (stiffness)
 - Coefficient of thermal expansion (soft or brittle)
 - Glass transition (glass-to-rubbery transtion)
 - Micrographic analysis (fiber/resin morphology)
 - Raman spectroscopy (residual stress)
- Liner tests
 - Tensile strength and stiffness
 - Fatigue
 - Microstructural analysis

Source of aged coupons samples



S/N 29 - Columbia vessel

- 25 years old
- Survived reentry
- Interior provided good samples



S/N 11

- 25 years old
- Not exposed to space
- Extensive pressure cycling

Coupon testing – Summary and Conclusions



- Tensile strengths for unaged and aged composite strands shows no significant difference
- Thermal Analyses for unaged and aged composites shows no significant differences in T_g

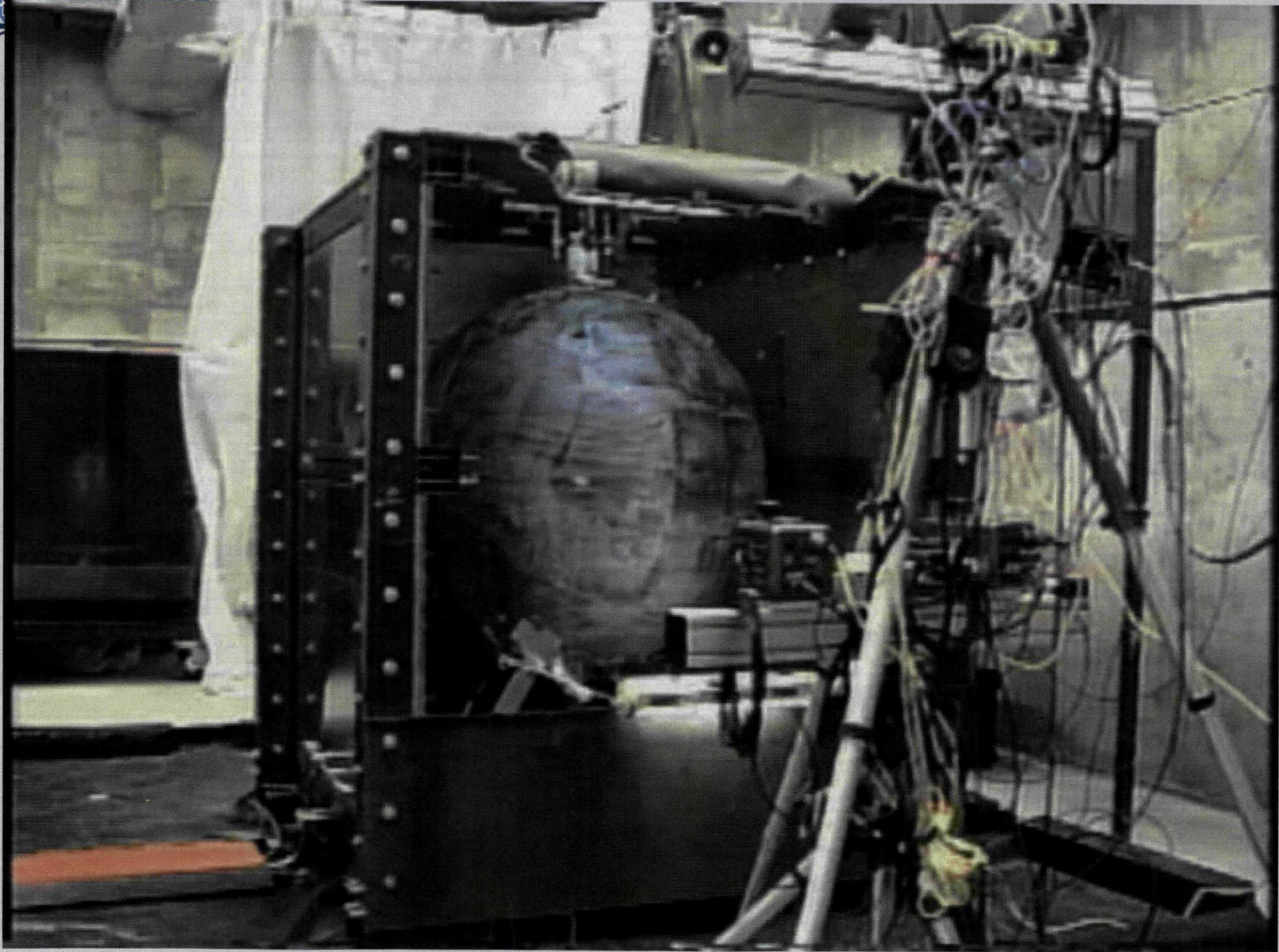
- The most substantial source of data concerning COPV stress rupture was a test program conducted at LLNL involving over 100 Kevlar wrapped vessels.
 - Testing was relatively uncontrolled, leading to inconclusive results
 - Follow-on program performed at NASA JSC on a smaller number of vessels – not enough data to support statistical modeling
- Considerable review of all the available COPV stress rupture data was used to develop a stress rupture reliability model
- The model uses the specific characteristics of each individual COPV to predicts its stress rupture reliability
 - Survived time at Maximum Expected Operating Pressure (MEOP)
 - Expected time at MEOP for next or future usage
 - Stress Ratio of the Kevlar (operating stress divided by ultimate stress)
 - Model parameters derived from COPV test data
- The stress rupture reliability model predicts Orbiter is flying with a mean reliability of greater than 0.999 per flight and greater than 0.99 for the remainder of the Space Shuttle Program.

- A key factor in the stress reliability model is the Stress Ratio

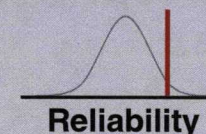
$$\text{STRESS RATIO} = \frac{\text{Stress in Overwrap @ MEOP}}{\text{Stress in Overwrap @ Burst}}$$

- The stress at burst varies from vessel to vessel, therefore the discrete stress ratio varies from vessel to vessel
- Stress ratio curves were developed in a conservative matter using test results from several Orbiter COPVs
 - The 40" diameter spheres were determined to have the highest stress ratio.
 - "Older" Main Propulsion Test Article (MPTA) COPV
 - Several cycles to MEOP (fast and slow) followed by a burst test
 - Health check of four 40" diameter spares

Why do a test?



- Space Shuttle Program directed a test to compare Orbiter COPV performance to the reliability model predictions because:
 - Reliability model is based on data from test articles that differ from flights COPVs
 - Manufacturing, material & pressure cycle are different from flight qualified COPVs
 - No full-scale, flight qualified, Orbiter COPV stress rupture test data existed
- Due to limited resources the test program was limited to a single COPV
 - A single data point will not validate the current model but could provide confidence in model predictions
- An accelerated test was designed
 - Selected test article removed from service and believed to be “worst flight tank”
 - Starting at maximum operating pressure of 4850 psi
 - Elevated temperature
 - Pressure and/or temperature increased in phases
 - Orbiter Project goal to reach 95% chance of failure





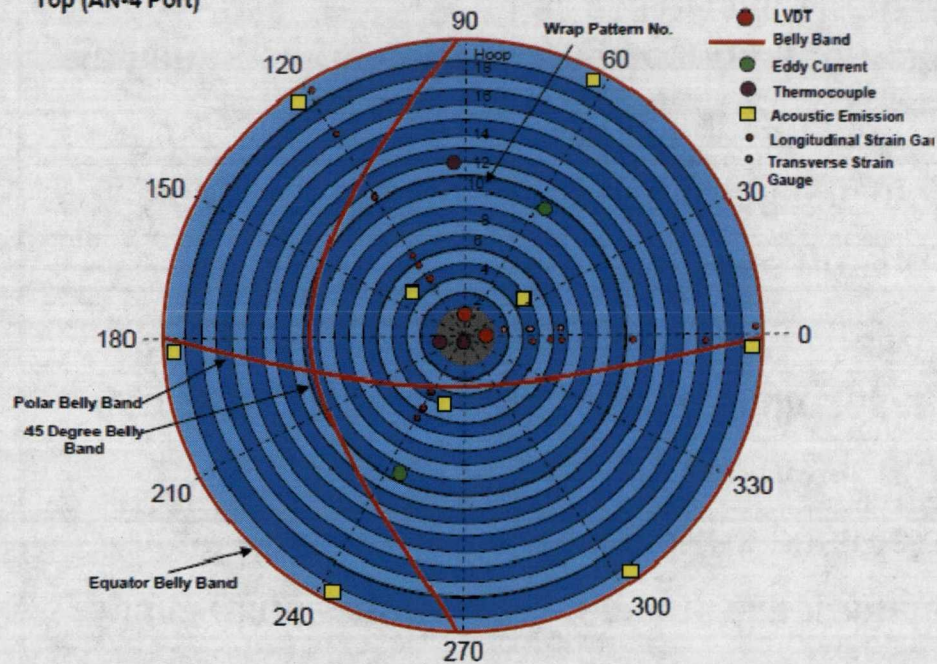
WSTF Test Cell, thermally controlled test cell with generator back-up. Precludes thermal control concerns akin to those of the LLNL tests.



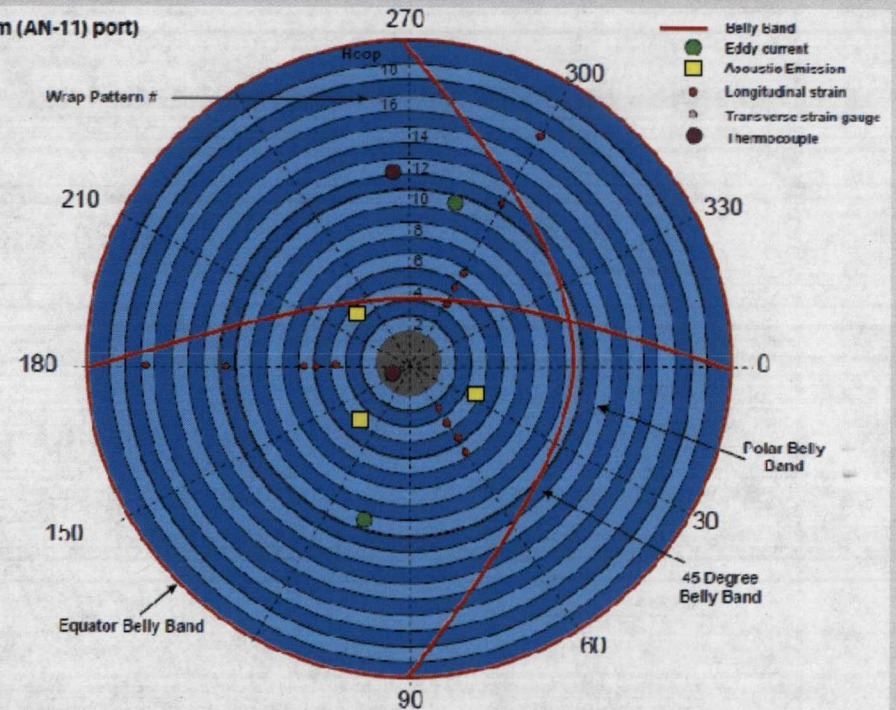
OMS/MPS test article in test frame. Allows freedom of movement to monitor vessel dimensional changes during test.

Test/Measurement	Purpose
Fluid Temperature	Test control parameter
Fluid Pressure	Test control parameter
Belly Bands	External diameter measurement
Acoustic Emission	Pinpoint failure location (triangulate)
Strain Gauges	Outer surface strain
Axial LVDT	Boss-to-boss growth
Eddy Current	Through wall thickness change
Video/Audio	Test documentation
Raman Spectroscopy	Engineering information – NDE development for external residual stress elastic strain

Top (AN-4 Port)

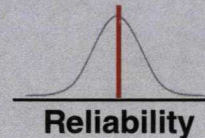


Bottom (AN-11) port)



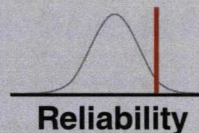
- Phase I

- Pressure: 4850 psi
- Temperature: 130°F
- Time: 38,000 effective hours
- Result: Tank passed with no issues
- Model Prediction: 50% chance of failure



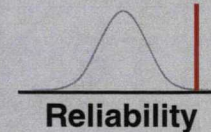
- Phase II

- Pressure: 4850 psi
- Temperature: 160°F
- Time: 87,000 effective hours
- Result: Tank passed with no issues
- Model Prediction: 95% chance of failure



- Phase III

- Pressure: 5200 psi
- Temperature: 160°F
- Time: 113,000 effective hours
- Result: Tank passed with no issues
- Model Prediction: 99% chance of failure

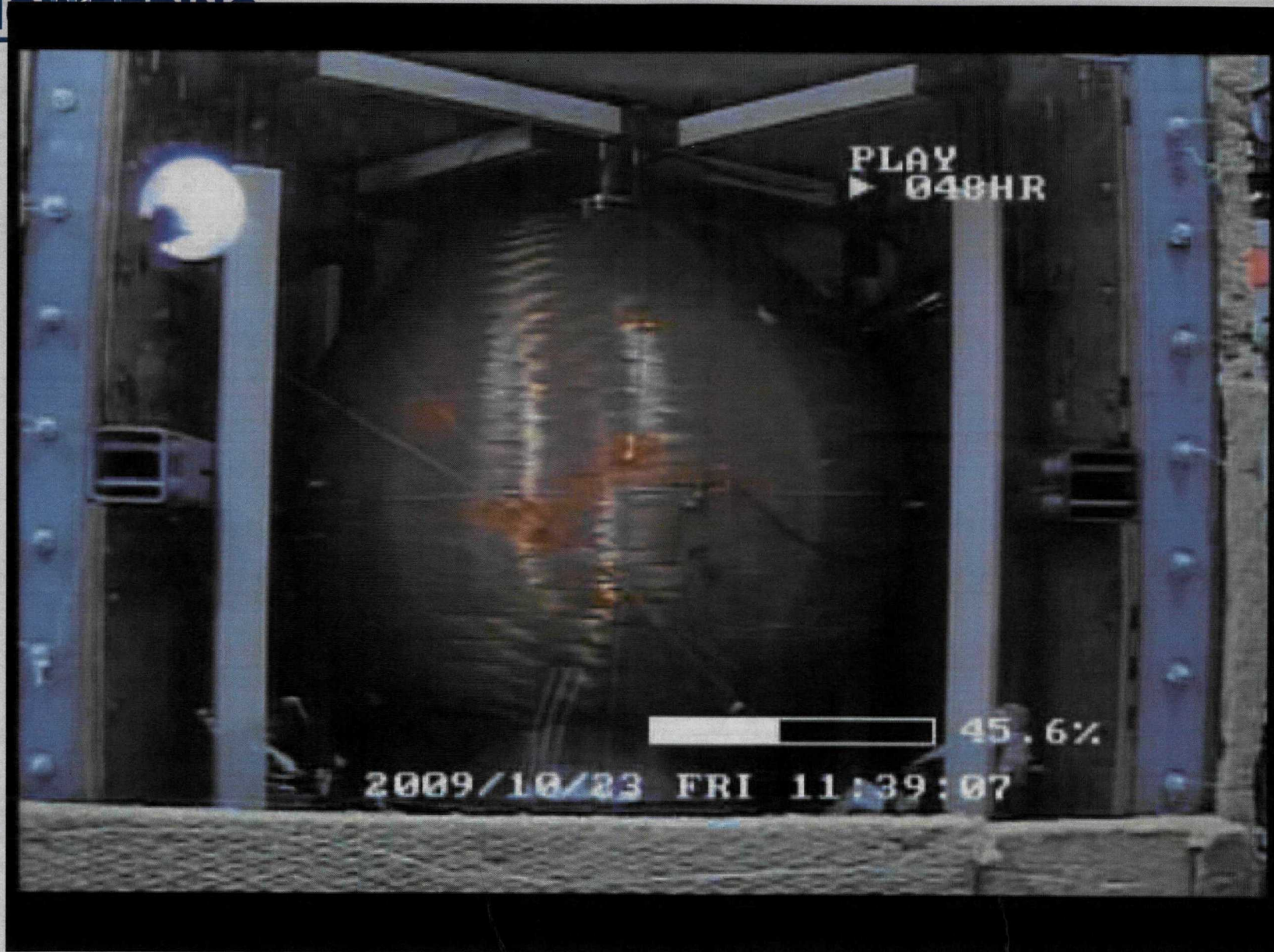


- Phase IV

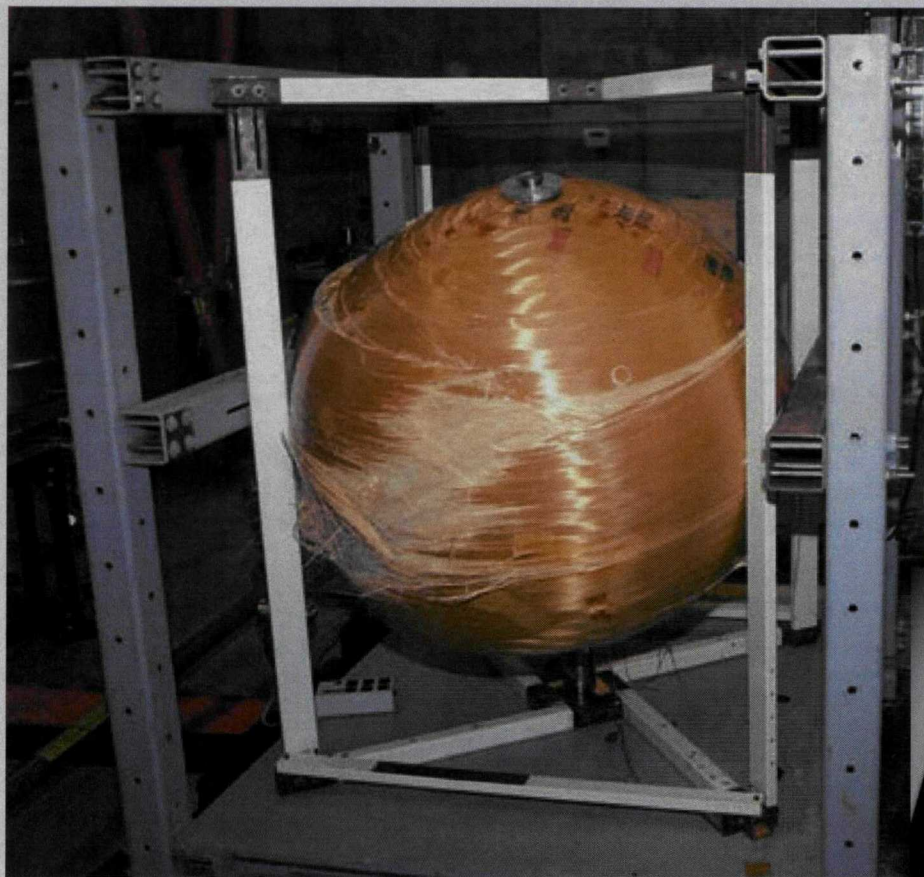
- Pressure: 5400 psi
- Temperature: 174°F
- Result: Tank failed after 3,100,000 effective hours

After Phase II Reached Orbiter Project Objective!

Test Results



Post test photos



Post test photos



- Test was the first experimental determination of tank lifetime (industry wide) on a flight-qualified COPV
- Testing of a flight article (exposed to space environments) proves no missed physics (confirms analysis)
- Provided best model confirmation, given validation not possible
 - Proper validation would require ~30 tanks
- Open questions
 - Was the “worst flight tank” the best test article?
 - Energizer bunny or demonstration of overstatement of risk?
 - How accurate was the prediction of stress ratio?
 - Off by 20%
 - How accurate is the model?
 - Specifically Age acceleration calculations

- A failure analysis is planned with the following objectives:
 1. Confirm Stress Rupture as the failure mode
 2. Compare Kevlar properties to previous aging study
 3. Investigate the condition of the liner
 4. Look at comparative NDE data
 5. Study instrumentation for indicators for future health monitoring of COPVs